# Measuring and tuning the performances of the acoustic guitar

*by Giuliano Nicoletti*

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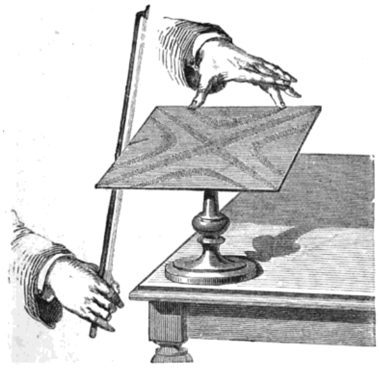
# Introduction

The acoustic guitar roots its tradition into the antiquity of human cultures. Arabic oud was played in Central Asia, North Africa and the Middle East several thousand years ago; the European lute was probably the most popular instrument in Europe during the Renaissance, 600 years ago, and the romantic guitar, as it was built in Paris in the early 1800s, was structurally identical to the acoustic guitar of our day. In all of these instruments the sound is generated by the transmission of vibrations from a set of strings to a soundboard, amplified at low frequencies by the resonance of a volume tuned by one or more openings of various shapes. Its evolution over the centuries has therefore been minimal, confirming a valid principle of operation: the little energy supplied to the strings allows in fact to generate a sound of intensity similar to that of a man's singing, a perfect accompaniment. On the other hand, exceptional progress has been made in the understanding and analysis of the physical phenomena that allow the guitar to generate sound. In 1687 Sir Isaac Newton published the book *Philosophiae naturalis principia mathematica*, the text that laid the foundations of classical mechanics, and that is still used today to describe the resonant system of the guitar. In 1787 Ernst Chladni described in his book *Entdeckungen über die Theorie des Klanges (Discoveries in the Theory of Sound)* a technique to show the modes of vibration of a rigid surface, known as Chladni figures - or Chladni patterns - due to the shapes or patterns created by various modes.

Arabic oud

Romantic guitar



Stroking a violin bow over the edge of a plate of metal covered with sand excite its resonances and causes the sand to move and concentrate along the nodal lines. The Chladni patterns.

In 1863 Hermann Von Helmholtz published: *Die Lehre von den tonempfindungen* (*About the feeling of tone as a basis for music theory*), describing the use of a system of acoustic resonators to analyze the spectral content of different sounds present in music. In the same period Jean Baptiste Fourier (councilor of Napoleon Bonaparte and director of the Polytechnic of Paris) developed the mathematical model of the Fourier Series, periodic functions composed of sinusoids in harmonic relation, which are still today the basis of the transformation of a sound from the time domain into that of frequency (FFT, fast Fourier transform).

Selection of Helmholtz resonators, 1870

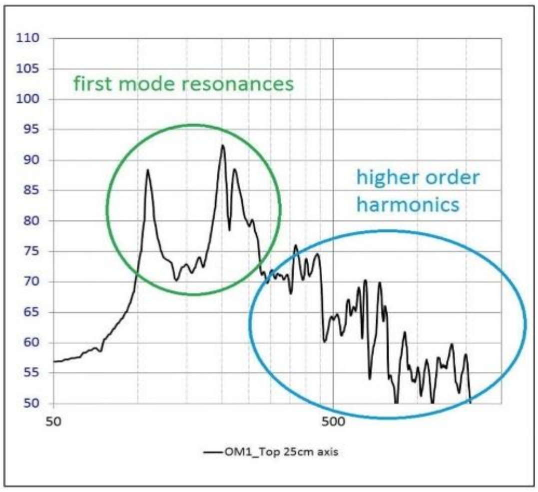
Minimal acoustic measurement setup.

Four industrial revolutions later, the development and democratization of digital computing offer an exceptionally powerful and cost-effective analysis platform. Any laptop can be connected to a USB microphone and through a freeware software offer accurate and repeatable measurements of the frequency response of an acoustic instrument, combining subjective evaluation with objective data.

# 1 Why should we measure?

## 1.1 The Value of Data Collection

The frequency response of the acoustic guitar can be considered the fingerprint of the instrument, its identity card; as will be shown later, it offers information on the spectral balance, the perceived dimension of the instrument and the complexity of the timbre. It allows to correctly position the frequencies of the fundamental resonances with respect to the tempered scale played on the fretboard of the instrument, thus minimizing the production of wolf notes, and improving the intonation. Over time, a valuable archive can be created through the collection of the measurement data, useful to correlate the best instruments with an objective evaluation, and to combine the memory of a sound with comparable data.




Frequency response of an acoustic guitar model OM; in evidence the peaks related to the first modes and to the higher order modes.

## 1.2 The Value of Accuracy and Repeatability

The precise measurement of resonant frequencies allows the builder to tune these resonances relative to the tempered scale played on the fretboard of the instrument; by tuning the guitar's resonances to minimize their interference with the fretted notes of the scale, the production of wolf notes can be minimized and the intonation of the instrument improved. The range of frequencies in which these main resonances fall, across all types of acoustic guitars (small classicals to large-bodied steel strings), runs from roughly 80Hz to 300Hz. Table 1 provides the notes of the tempered scale, with their related frequencies, in relation to the fretboard and strings of the acoustic guitar, tuned in standard tuning.

The table shows that the frequency intervals of the semitones of the notes around 90 Hz (F2 – F#2) and 260 Hz (B3 – C4), are 5.19 Hz and 14.69 Hz, respectively. Since the aim of tuning the body resonances is to place them exactly in between adjacent notes, it is clear that resonances need to be tuned to a 1 Hz [1] accuracy. Performing such a delicate tuning by ear is extremely difficult. On the other hand, this is precisely the field in which the measurement excels, identifying the resonances with precision and reliability.

| Fret Number | | | | | | Note | Frequency |
|---|---|---|---|---|---|---|---|
| 6th String | 5th String | 4th String | 3rd String | 2nd String | 1st String | | (Hz) |
| Open | | | | | | $E_2$ | 82,4 |
| 1st | | | | | | $F_2$ | 87,3 |
| 2nd | | | | | | $F^{\#}_2/G^{b}_2$ | 92,5 |
| 3rd | | | | | | $G_2$ | 98,0 |
| 4th | | | | | | $G^{\#}_2/A^{b}_2$ | 103,8 |
| 5th | Open | | | | | $A_2$ | 110,0 |
| 6th | 1st | | | | | $A^{\#}_2/B^{b}_2$ | 116,5 |
| 7th | 2nd | | | | | $B_2$ | 123,5 |
| 8th | 3rd | | | | | $C_3$ | 130,8 |
| 9th | 4th | | | | | $C^{\#}_3/D^{b}_3$ | 138,6 |
| 10th | 5th | Open | | | | $D_3$ | 146,8 |
| 11th | 6th | 1st | | | | $D^{\#}_3/E^{b}_3$ | 155,6 |
| 12th | 7th | 2nd | | | | $E_3$ | 164,8 |
| 13th | 8th | 3rd | | | | $F_3$ | 174,6 |
| 14th | 9th | 4th | | | | $F^{\#}_3/G^{b}_3$ | 185,0 |
| 15th | 10th | 5th | Open | | | $G_3$ | 196,0 |
| 16th | 11th | 6th | 1st | | | $G^{\#}_3/A^{b}_3$ | 207,7 |
| 17th | 12th | 7th | 2nd | | | $A_3$ | 220,0 |
| 18th | 13th | 8th | 3rd | | | $A^{\#}_3/B^{b}_3$ | 233,1 |
| 19th | 14th | 9th | 4th | Open | | $B_3$ | 246,9 |
| 20th | 15th | 10th | 5th | 1st | | $C_4$ | 261,6 |
| | 16th | 11th | 6th | 2nd | | $C^{\#}_4/D^{b}_4$ | 277,2 |
| | 17th | 12th | 7th | 3rd | | $D_4$ | 293,7 |
| | 18th | 13th | 8th | 4th | | $D^{\#}_4/E^{b}_4$ | 311,1 |
| | 19th | 14th | 9th | 5th | Open | $E_4$ | 329,6 |
| | 20th | 15th | 10th | 6th | 1st | $F_4$ | 349,2 |
| | | 16th | 11th | 7th | 2nd | $F^{\#}_4/G^{b}_4$ | 370,0 |
| | | 17th | 12th | 8th | 3rd | $G_4$ | 392,0 |
| | | 18th | 13th | 9th | 4th | $G^{\#}_4/A^{b}_4$ | 415,3 |
| | | 19th | 14th | 10th | 5th | $A_4$ | 440,0 |
| | | 20th | 15th | 11th | 6th | $A^{\#}_4/B^{b}_4$ | 466,2 |
| | | | 16th | 12th | 7th | $B_4$ | 493,9 |
| | | | 17th | 13th | 8th | $C_5$ | 523,3 |
| | | | 18th | 14th | 9th | $C^{\#}_5/D^{b}_5$ | 554,4 |
| | | | 19th | 15th | 10th | $D_5$ | 587,3 |
| | | | 20th | 16th | 11th | $D^{\#}_5/E^{b}_5$ | 622,3 |
| | | | | 17th | 12th | $E_5$ | 659,3 |
| | | | | 18th | 13th | $F_5$ | 698,5 |
| | | | | 19th | 14th | $F^{\#}_5/G^{b}_5$ | 740,0 |
| | | | | 20th | 15th | $G_5$ | 784,0 |
| | | | | | 16th | $G^{\#}_5/A^{b}_5$ | 830,6 |
| | | | | | 17th | $A_5$ | 880,0 |
| | | | | | 18th | $A^{\#}_5/B^{b}_5$ | 932,3 |
| | | | | | 19th | $B_5$ | 987,8 |
| | | | | | 20th | $C_6$ | 1046,5 |

Table 1: The scale notes and related frequencies of the guitar fretboard, in standard tuning

[1] Trevor Gore; *Contemporary acoustic guitar design and build*, section 1.4.7, Mechanical impedance.

Sinusoidal generator, audio amplifier, small fullrange speaker: that’s all it takes to let the basil leaves dance over the soundboard to reveal the figures of Chladni and its hidden secrets.

## 1.3 The Value of visualisation

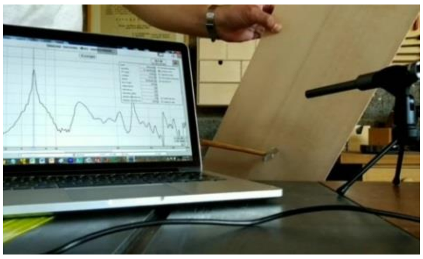
The visualization of Chladni figures gives a very useful insight about the behaviour of the bracing system, the way it shapes the frequency response and the sound of the instrument. The setup required to make this measurement is simple and inexpensive, and will be described in detail in a later article.

## 1.4 The Value of mechanical and acoustical measurements

The measurement of the monopole mobility, the equivalent mass of the soundboard and its compliance actually lays the foundation of the optimization of the guitar responsiveness, always in the search for the perfect balance between stability of the guitar structure and lightness of vibrating surfaces. This parameter is derived from the soundboard T(1,1)2 mode - decoupled from the acoustic resonance of the internal volume - and from the measurement of the deflection of the soundboard by means of a precision micrometer on a jig. This parameter is of primary importance and characterizes with a very simple and clear data the efficiency and reactivity of the instrument as a whole.

A dedicated jig with a micrometer and a weight is the setup necessary to measure the compliance of the soundboard, and then calculate the monopole mobility.

Measuring the characteristics of the wood through acoustic analysis of the tap-tone permits to obtain very precise mechanical datas, which can be used to optimize the engineering of the instrument. Over time the database of materials will become richer and richer, and will also allow to keep track of any evolution of the characteristics of the woods due to aging, humidity and temperature.



Measurement of the first longitudinal mode of the panel, Umik-1 USB microphone, REW software

Much more will surely come with time, practice and experience: “*It is not the intention of this little book to stifle creativity or to reduce it to a bunch of rules. It is not the formula that prevents good design from happening but lack of knowledge of the complexity of the Design profession. It’s up to the brain to use the proper formula to achieve the desired result.*” Massimo Vignelli, The Vignelli Canon.

## 2 A bit of theory of sound and its propagation

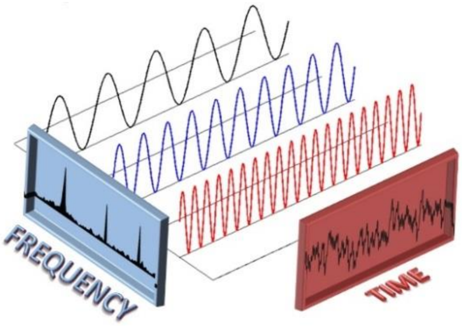
Sound, as it is perceived by our hearing is made up of vibrations that propagate in the air as acoustic waves, reach the auditory system and are transformed by our brain into perception; the frequencies of these vibrations are between 20 Hz (20 oscillations per second) and 20 kHz (20,000 oscillations per second). Below this range is the infrasound, real telluric vibrations, and above is the ultrasound, perceptible exclusively by some animals. The sound travels in the air at about 344 meters per second, and in other mediums (such as the soundboard of an acoustic guitar) with a speed determined by the density and rigidity of the material that makes up the medium itself: the softer and denser the medium, the slower the sound is transmitted inside it, and vice versa. The speed of sound through rubber is 60 meters per second, within spruce around 5500 m/s along the fiber and 1500 m/s across the fiber; in Beryllium the sound travels at 12000 m/s (and that's why at Focal we use this material for the membranes of tweeters).

Acoustic waves are generated when a surface vibrates, and transmits these vibrations to the surrounding environment: when the strings are pinched by the fingers, they exert a force on the bridge and then on the soundboard (by mean of longitudinal and transverse waves), which in turn is made to vibrate and produces sound. The large vibrating surface of the soundboard is able to move an important amount of air particles, and therefore to generate acoustic waves of sufficient intensity to perceive a sound with volume and projection (compared to the volume generated by the strings alone), especially in the frequencies contiguous to the main resonances of the soundboard (and the resonance of the volume of air contained in the box).

| dB | Power ratio | Amplitude ratio |
|---|---|---|
| 100 | 10000000000 | 100000 |
| 90 | 1000000000 | 31623 |
| 80 | 100000000 | 10000 |
| 70 | 10000000 | 3162 |
| 60 | 1000000 | 1000 |
| 50 | 100000 | 316 |
| 40 | 10000 | 100 |
| 30 | 1000 | 31 |
| 20 | 100 | 10 |
| 10 | 10 | 3.16 |
| 6 | 4 | 2 |
| 3 | 2 | 1.4 |
| 1 | 1.26 | 1.1 |
| 0 | 1,0 | 1 |

Conversion table between dB, power ratio, amplitude ratio.

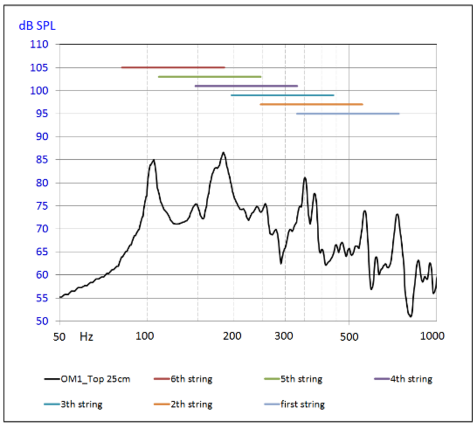
The sound pressure level (the perceived volume of a given sound) is measured as the ratio of a certain sound pressure and the silence threshold (the faintest sound perceptible by a young man with excellent hearing); the silence threshold is established by convention at 20 microPa (Pascal is the unit of measurement of pressure), and to express this ratio the unit of measurement decibel SPL (dB SPL) is used. The dB is a logarithmic scale of measurement, and is suitable to describe the sensation of volume of a sound precisely because our hearing has an exceptional sensitivity, from noises of very small intensity to a strike thunder in the vicinity. A normal conversation takes place at around 60 dB (0.02 Pa), the sound of a loud stereo system at 90 dB (0.63 Pa), thunder at 130 dB (63.2 Pa), the engine of a Jet at 150 dB (632 Pa). If the sky fell on our heads the sound level would be 194 dB (101.325 Pa, the atmospheric pressure at sea level). A doubling of acoustic power is equivalent to +3 dB SPL.



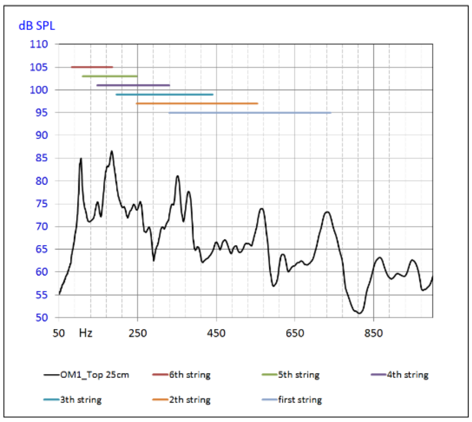

Relationship between time domain and frequency domain.

## 2.1 How to visualize sound?

There are mainly two possible methods of visualizing a sound in a Cartesian graph: in the time domain and in the frequency domain. In the first case we report on the axis of the ordinates, Y, the sound pressure level in dB SPL, and on the axis of the abscissas, X, the time in seconds. This graph is usually used to display pulses, and provides information on the temporal decay of a sound; useful for example to visualize the qualities related to the sustain of an acoustic instrument. In the second case we always keep the unit dB SPL on the ordinates, while on the abscissa we report the frequency value, in Hertz (Hz); this graph is used to analyze the spectral content of a sound: the equilibrium in which low, medium and high frequencies compose it. We use this graph to visualize the frequency response of a hifi speaker or, as in this case, of an acoustic guitar. It is always recommended to maintain a logarithmic scale even on the abscissas axis, because this scale represents our way of discriminating the various frequencies better than a linear scale, and makes it easier and more immediate to read and interpret it.




Logarithmic X-axis




Linear X-axis

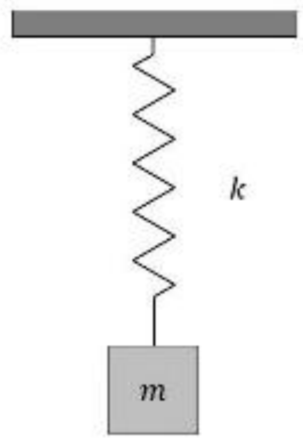
In the two graphs above are displayed: OM guitar frequency response and frequency ranges of the six strings of the acoustic guitar in the first six frets. The comparison between logarithmic VS linear X-scale highlights how the logarithmic scale is more suitable for the human auditory system: the spacing of the six notes is homogeneous, and the main resonances have similar shape throughout the frequency range.

It is very important to correctly set the scales of the two axes: the optimal values are obtained when the graph occupies all the available space in a readable way, and it is therefore possible to easily discern the most interesting data at first glance: for the analysis of an acoustic guitar, the most interesting frequency range is located between 50 and 1000 Hz, and 50-60 dB of dynamic range on the y axis offer a correct spacing. It is also always recommended, as far as possible, to keep the same scaling of the two axes, to have ease of comparison between

different measurements made at different times; always pay attention to the values of the reference scale of the axes: the same curve can look very different (and be misinterpreted) if presented on different axes scales.

# 3 How does the acoustic guitar work?

The energy supplied to the strings through the fingers, or the plectrum, is transmitted to the soundboard via the bridge and the saddle; the soundboard vibrates, and excites into motion the air particles in contact with it, amplifying the sound of the strings especially on the low frequencies of the sound spectrum of the instrument. The transmission of energy between the strings and the soundboard is a delicate and complex process; unlike one can imagine, the vibrations transmitted to the soundboard are not constant over a wide range of frequencies (as for example happens with the membrane of a HiFi loudspeaker, whose task is to reproduce as faithfully as possible the signal applied to its terminals); most of the energy is instead concentrated in very narrow bands, in the surroundings of the frequencies of the main resonances of the guitar body, where the mechanical impedance is minimal and the soundboard is very sensitive to the stimulus applied.



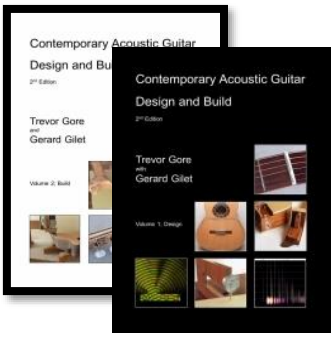

m is the inertial mass of the oscillating body, k is the spring constant of elasticity

Resonance is a physical phenomenon that occurs when an oscillating system is subjected to an external force and starts moving producing a harmonic motion; the most common example is that of the mass-spring system: pulling and releasing the mass the system is put in motion and oscillates with a frequency determined by the mass and the constant K of spring elasticity; the energy is cyclically converted into kinetics (when the mass moves) and potential (when the spring extends or compress).

The resonance frequency is also called the natural frequency, and is expressed by the simple equation:

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

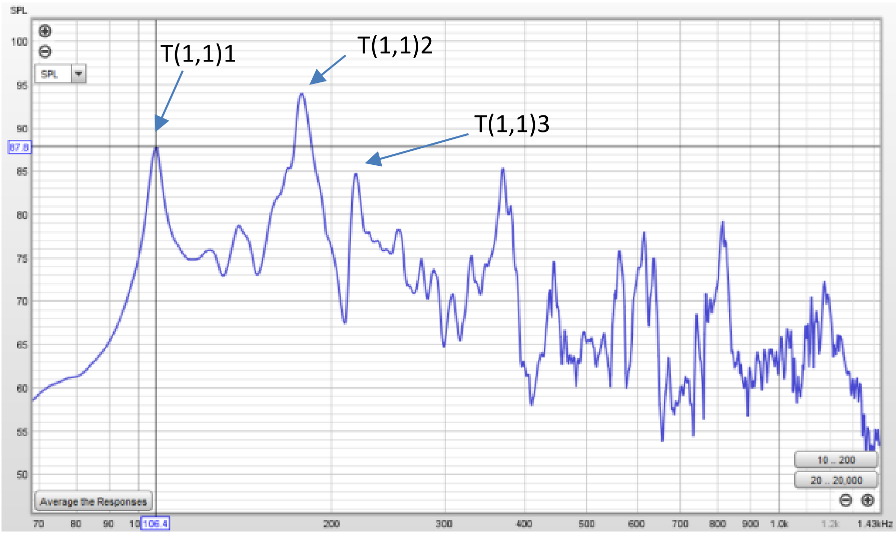
Eventually, the acoustic guitar being a complex set of mass-spring systems, and being the mechanical admittance of each of these resonator maximal at the resonance frequency, the response of the instruments will be characterized by a series of distincts peaks; by making




some simplifications we can get to define its behaviour with a good degree of approximation. This simplification approach is very often used to describe complex systems, to understand their working principles, the interactions between the parts and to effectively manage their most important parameters.
For those who want to deepen the topic we suggest the purchase of the excellent manual by Trevor Gore and Gerard Gilet: *Contemporary Acoustic Guitar Design and Build.*[2]

### 3.1 Main resonances of acoustic guitar

Let's observe the plot of the frequency response of an acoustic guitar, highlighting the first three main resonance modes: the acoustic resonance mode T(1,1)1, the main resonance of the soundboard T(1,1)2 and the main resonance of the back of the instrument T(1,1)3.




The nomenclature of resonance modes is not unequivocal, and a recognized international standard has not been developed yet. In this document we use the nomenclature developed within the musical acoustics research group of the University of Cardiff from about the 1980s[3], which seems the most complete for the acoustic guitar and the most used in the international community. However, other classifications are widely used for acoustic instruments, beginning with the studies of Ian Firth[4], up to the numerous publications of the University of Maine, France.

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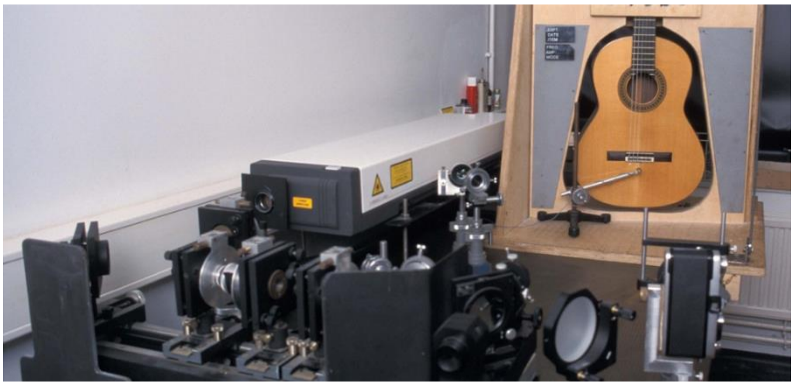
[2] The book "Contemporary Acoustic Guitar Design and Build, 2nd Edition", Trevor Gore et Gerard Gilet, is made of two tomes, on the design and the construction of the instrument. It is available both on Stewmac catalogue and on the author's website: https://goreguitars.com.au/main/page_the_book_overview.html
[3] B. E. Richardson; *A physical investigation into some factors affecting the musical performance of the guitars*, 1982; *Input admittance and sound field measurements of ten classical guitars*, 2002.
[4] Ian M. Firth; *Physics of the guitar at the Helmholtz and first top-plate resonances,* 1976.

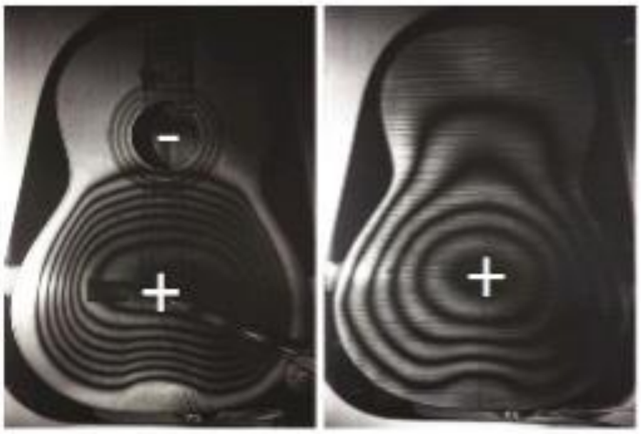


Here is the laser interferometry system developed and used by the acoustic research team at Cardiff University to study the physics of stringed instruments.

To clearly visualize these three resonances we will use images from a paper published in 2010 by Bernard Richardson, and made through the use of a laser interferometry system developed in the late sixties.

In the words of the author: *finally, it might be noted that holographic interferometry is not an easy technique to use. To call it temperamental is an understatement. At its best, however, it produces images of quite stunning beauty with* a *wealth of technical content.*[5]

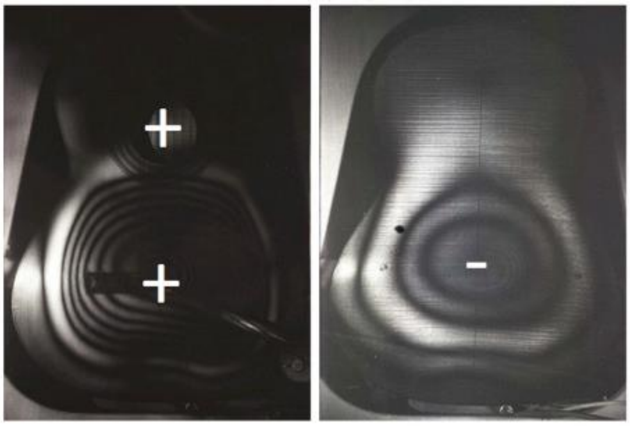
And it is certainly true that these are useful and interesting images: they offer indications not only about the shape of the resonances and the area of the instrument they cover, but also of their amplitude, proportional to the quantity of the lines. The author has eventually added the sign with the polarity of emission, thus giving with the amplitude information also that of the acoustic phase.




Resonance modeT(1,1)1 ; soundboard and back are activated by this resonance, in phase opposition.

Starting from low frequencies, the lowest notes reproduced by the guitar, **the first resonance** we encounter T(1,1)1 is the one produced by the mass of the volume of air contained in the opening of the rosette (although it may appear thin, it still has a volume) that bounces off the air spring contained inside the box; it is a resonance similar to that which occurs in Helmholtz resonators, with the difference that with this resonance are also coupled the one of the soundboard and - often but not always - the back of the instrument. The easiest way to verify that this peak is produced by this resonance is to close the hole and repeat the measurement: the confirmation will be the disappearance of this first peak, and a slight downward shift of the second T(1,1)2 resonance.

[5] B. E. Richardson; *Mode studies of plucked stringed instruments: application of holographic interferometry,* Proceedings of the Second Vienna Talk, Sept. 19–21, 2010

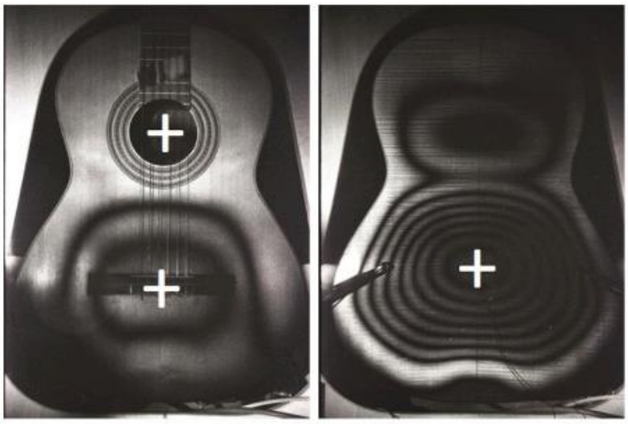


Resonance mode T(1,1)2, the main mode of the soundboard. The back is in phase opposition, much smaller amplitude.

**The second resonance** that is usually positioned higher in frequency is the one produced by the monopole of the soundboard, T(1,1)2; in this case the mass is that of the central area of the soundboard, the compliance is that of the outer area of the board and part of the bracing system, which behaves similarly to the suspension of a cone speaker.

This mode of resonance is what usually produces most of the sound of the instrument. Its intensity and the frequency at which it is produced are probably the two parameters that most influence the instrument's timbre. In case of doubt, the easiest way to verify the origin of this resonance is to stick a mass of about 25 grams in the center of the bridge and repeat the measurement, to verify if a lowering of the frequency takes place (of about 10 Hz in the case of an average instrument with an equivalent mass of the top of around 70 grams).

**The third resonance** that we can encounter is T(1,1)3, produced by the back of the instrument. The back of the instrument is not excited directly by the strings, but mainly through the acoustic coupling with the soundboard, and therefore the intensity of this resonance is usually lower than that of the soundboard. If the back is heavy and stiffened by ridged bracing, then its acoustic contribution tends to disappear.



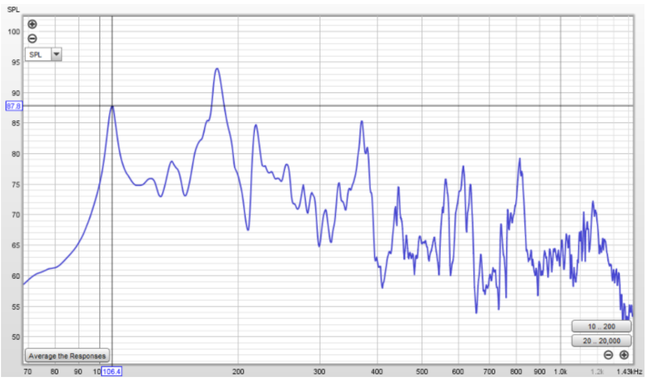
Resonance mode T(1,1)3 ; it is the mode of the back, in phase with the soundboard, and therefore participates in the overall emission of the instrument.

It can happen sometimes, in some particular instruments such as the gypsy guitars, that have a very thin back - that the two resonances of the soundboard and the back are reversed; it is always recommended in case of doubt to make a measurement in the near field, 5 cm from the board, to highlight the acoustic resonance produced by that particular active area of the instrument. Also in this case, a mass of 25 grams stuck in the center of the plate will produce a lowering of the frequency of this mode.
The degree of activity of the back of the instrument is a parameter determined in the design phase by the constructive choices, and it is probably safer to have a passive back than a

resonance too close to that of the soundboard (which could make the delicate and important resonance T(1,1)2 lose clarity). There are also important structural considerations that must be considered, especially in folk guitars, subjected to considerable mechanical stress due to the continuous tension of the strings set.

These first three modes define the character of the instrument, they are the easiest to manage during the design and development phase, and therefore deserve special attention.

# 4 Mastering the frequency response of the acoustic guitar



Frequency response curve of an acoustic guitar measured by REW software and UMIK-1 microphone

Once a correct, clean and repeatable curve has been acquired (see Appendix A), the process of analysis and interpretation can begin, which will lead us to gather information that can guide us in the process of development of the instrument, and verification of the design and construction choices: the positioning of the main resonances, the effectiveness of a new bracing structure, or a new shape of the body. Some details will be immediately evident, others need to be carefully analyzed.

With the aim to make this important part of the analysis process fluid and reliable, we list below a basic checklist to follow in order to quickly obtain the most important informations; further insights not present in this list are obviously possible and will be the subject of future work. We will then describe what we believe to be the most important parameters to check, how to read the results, and then provide basic indications on how to correct any problems encountered.

Here are the points of the basic checklist, sorted by importance and simplicity of measurement:

- **Identification of the frequencies of the main resonance modes**
    - *Do the frequencies of the main modes respect the acoustic choices of the project?*
    - *Can the distribution of the first modes result in the production of wolf notes?*
    - *Are the frequencies of the first modes following a harmonic series?*
    - *Presence and breadth of higher-order modes*

- **Visualizing Chladni Figures**
    - *Arrangement of resonances on the boards*

- **Measurement of monopole mobility**
    - *Effective mass of the soundboard*
    - *Sagging of the soundboard*
    - *Mobility factor of the monopole*

## 4.1 Do the frequencies of the main modes respect the project acoustic choices?

| Air resonance T(1,1)1 | | |
|---|---|---|
| classical | acoustic | archtop |
| 90 - 110 Hz | 80 - 110 Hz | 100 - 150 Hz |

| Soundboard monopole T(1,1)2 | | |
|---|---|---|
| classical | acoustic | archtop |
| 190 - 220 Hz | 160 - 200 Hz | 200 - 250 Hz |

| Back monopole T(1,1)3 | | |
|---|---|---|
| classical | acoustic | archtop |
| 230 - 250 Hz | 220 - 240 Hz | 250 - 300 Hz |

Here is a table that shows the frequencies at which the first three modes are usually positioned in guitars of traditional structure.
These frequency ranges can be directly related to the general timbre of the instrument we are building: do we expect it to have a more robust and full-bodied sound, or do we look for more projection and presence on the mid-range?
The ideal instrument for any kind of music probably does not exist, and usually the luthier makes choices based on the type of guitar he is building. If it is a blues instrument then we will want to focus more energy on the mid-range (and therefore the mode T(1,1)2 around 200 Hz), and maintain a light and reactive soundboard; if strumming is the kind of preference then we will look for an instrument focused on the mid-bass and still possibly powerful and reactive: (T(1,1)1 above 100Hz and T(1,1)2 between 180 and 200 Hz. While if fingerpicking is required then a guitar balanced over the entire spectrum is required, possibly less prone to the production of wolf notes and with a good sustain (two parameters that can be related to the equivalent mass of soundboard): T(1,1)1 around 95 Hz, T(1,1)2 at 180Hz. Generally speaking also the aesthetics of the instrument should be adapted to its acoustics, so that the musician receives a unique and clear message (a big instrument would have a full and powerful sound, with lot of bottom end, while it’s not always the case). These considerations are probably taken for granted by many, but it is always worth repeating them.

## 4.2 Can the first modes result in the production of wolf notes?

One of the most unpleasant phenomena that can be present in acoustic instruments is that of the infamous wolf notes, often positioned right in the center of the fretboard, that sound unpleasant, dark, chuncky, with a very short sustain. This is an actual defect of the instrument, that should be avoided as much as possible.
So what does the possible presence of wolf notes depend on? As we have seen just above, the production of much of the acoustic energy emitted by the guitar is generated by the first two-three resonance modes that are produced by the sound box. These three modes cover the notes ranging from the low E – 82.4 Hz – to the first notes reproduced by the second string; here are some general considerations regarding the behaviour of these modes:

- The first mode T(1,1)1 and the monopole T(1,1)2 are highly active even in frequency ranges contiguous to their resonance frequency, and can serve a very wide frequency spectrum.

- Their sensitivity is maximum precisely at their resonance frequency, where the mechanical impedance is minimal. When the notes played have a frequency close to or corresponding to that of these resonances the energy provided by the strings is absorbed very quickly, because the mechanical impedance is very low. Notes tend to have a fast decay, less sustain, and dampen quickly.

- Moreover, when energy is supplied by another resonant system (such as a string, which resonates at a frequency determined by tuning) these two resonances interact. If the two frequencies are identical, or very similar, they tend to repel each other, increasing or decreasing their resonance frequencies.

The result of these two phenomena combined is the production of a wolf tone: a note that is placed on a resonance and sounds bad, without sustain, and does not stabilize on the tuning, oscillating around the frequency at which we would like to hear it play. This phenomenon is very evident on lighter soundboard, while guitars with a higher equivalent mass generally have a more homogeneous sound and are less critical in optimizing this parameter (is this also one of the reasons why commercial instruments are usually over-built?). We will address this topic in a future update of this article dedicated to the analysis of the mobility of the monopole T(1,1)2.

The best way to reduce the presence of wolf notes is to move the frequencies of the main resonances of the instrument exactly in between two contiguous notes of the musical scale; it is necessary to be very accurate - because the instrument may have tolerances related to humidity and temperature that slightly modify its frequencies of resonance - and position the frequency of the resonances with the highest possible accuracy.

Let's see in detail the range of frequencies usually available to position the first resonance, the air mode T(1,1)1:

| String | frequency (Hz) | note | mode T(1,1)1 |
|---|---|---|---|
| 6 | 82,4 | E | |
| | | | 85 |
| | 87,3 | F | |
| | | | 90 |
| | 92,5 | F# / Gb | |
| | | | 95 |
| | 98,0 | G | |
| | | | 100 |
| | 103,8 | G# / Ab | |
| | | | 107 |
| 5 | 110,0 | A | |
| | | | 113 |
| | 116,5 | A# / Bb | |
| | | | 120 |
| | 123,5 | B | |
| | | | 127 |
| | 130,8 | C | |
| | | | 134 |
| | 138,6 | C# / Db | |

And in a second table the range of frequencies usually available for the second resonance, the soundboard mode T(1,1)2.

| String | frequency (Hz) | note | mode T(1,1)2 |
|---|---|---|---|
| 4 | 146,8 | D | |
| | 155,6 | D# / Eb | |
| | | | 160 |
| | 164,8 | E | |
| | | | 170 |
| | 174,6 | F | |
| | | | 180 |
| | 185,0 | F# / Gb | |
| | | | 190 |
| 3 | 196,0 | G | |
| | | | 202 |
| | 207,7 | G# / Ab | |
| | | | 214 |
| | 220,0 | A | |
| | | | 226 |
| | 233,1 | A# / Bb | |
| | | | 240 |
| 2 | 246,9 | B | |
| | | | 254 |
| | 261,6 | C | |

### 4.2.1 How to shift the frequency of mode T(1,1)1?

As we have seen above, the frequency of the instrument's first resonant mode is determined by:

- Volume of active air inside the instrument soundbox
- Volume of air contained within the opening (if there are several openings, the sum of their volumes).
- Coupling with other nearest resonances, and therefore with the monopole T(1,1)2.

As we usually cannot change the volume of the box, the easiest way to shift this resonance is therefore to change the size of the opening, specifically the diameter of the soundhole; to lower the frequency it is necessary to reduce the size of the opening, vice versa to raise it it is necessary to increase its size, to increase the diameter of the soundhole. In a traditional dreadnought or OM guitar, 3mm difference on diameter shifts the resonance frequency by about 2Hz; as always, it is recommended to proceed with a gradual modification, measuring the results step by step.

### 4.2.2 How to shift the frequency of mode T(1,1)2?

The frequency of the first resonance mode of the soundboard, the monopole, is determined by:

- Equivalent mass of the soundboard (the amount of mass that actively participates in this resonance, about 60-70% of the total mass of the soundboard ).
- Equivalent compliance of the soundboard (rigidity of the bracing placed in the external area of the soundboard, constraints of the soundboard with sides, thickness of the soundboard along the edge).
- Adaptation of mechanical impedance of the soundboard with sides.
- Coupling with mode T(1,1)1.

The first two parameters suggest changes that are simple enough to implement.
Adding a little mass to the center of the monopole - inside the box, underneath the soundboard - is quite simple; of course, increasing the mass of the monopole involves a slight decrease in its efficiency, and we therefore suggest this approach only if it is necessary to decrease a couple of Hz (changing for example the material of the string pins).
Removing mass to increase the resonance frequency is a very delicate operation, and it is assumed that the mass of the soundboard with its bracing has already been reduced as much as possible during the construction of the instrument.
Modifying the equivalent compliance of the soundboard is also an effective modification, that can be applied during construction by reducing its thickness at the edge, as often suggested in the literature of traditional luthiery or as Taylor operates inside the sound box.

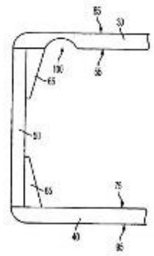
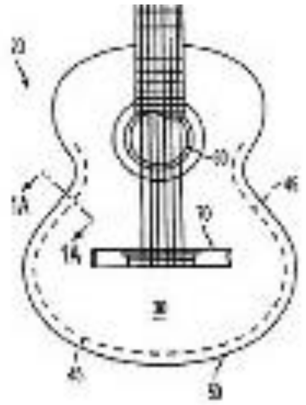


FIG. 3



One of the rare recent patents in the domain of acoustic guitars is filed under the name of Andy Taylor Powers, and describes a milling along the inner edge of the soundboard, with the aim of lowering its resonance frequency.

Once the construction is finished, it is possible to intervene by reducing the height of the bracing with a small fingerplane, passing through the soundhole. The braces to be carved are the central ones: in the case of an X-like Martin-type scheme, the most sensitive area is the scalloping of the lower part of the X and the two tonebars.

A magnificent instrument by luthier Theunis Fick, under construction; the back is designed to be active and on the sides there are supports with bolts to eventually add masses that allow to tune the mode T(1,1)2.

The third parameter is the adaptation of the mechanical impedance at the edge of the soundboard: the greater the difference in density, and therefore in mass, between the soundboard and the sides to which it is glued, the greater the amount of energy that will remain inside the soundboard, instead of being transmitted to the sides. Increasing the mass of the sides increase also the decoupling of the soundboard, its active surface and equivalent mass; as a result of these changes it will also lower the frequency of resonance. This modification can be made by keeping the possibility of adding masses within the sides: small bolts on inner lateral block allows to manage this parameter with a certain simplicity. Lowering the resonace frequency by about 2 Hz in a standard steel string guitar demands to add approximately 150 grams; it is suggested to add that mass very solidly at the opposite sides of the lower bout.

In this case as well the intervention allows to lower the frequency, but not to raise it. In general, it is always advisable to try to target slightly higher frequencies than the final

objective, in order to be able to adapt them easily. Going down too much with the resonance frequencies exposes to situations that can be difficult to solve.
Finally, remember that all the first modes are coupled with each other, especially the first two, and that therefore changing the frequency of one can produce a displacement of the others. Always keep an eye on the frequency response as a whole.

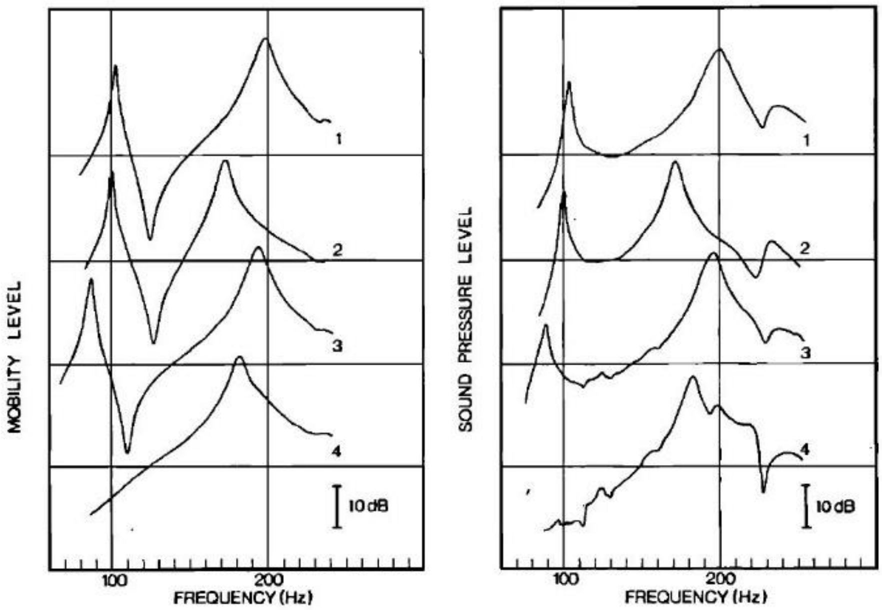
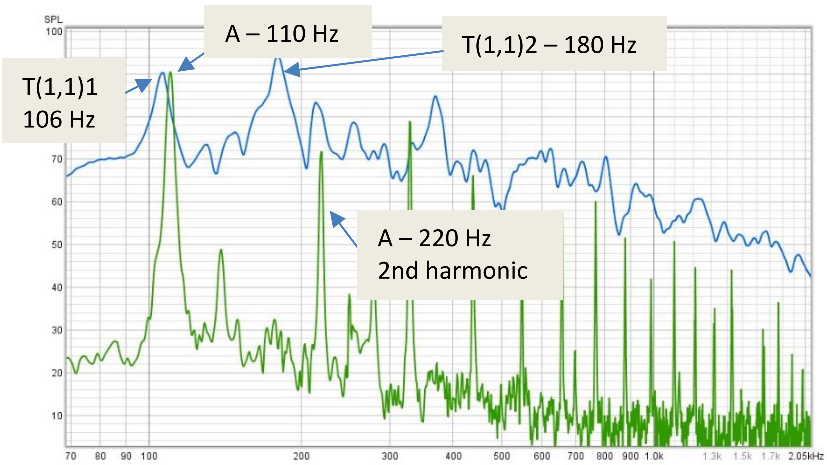



FIG. 1. The effect of specific changes in top plate resonance frequency and in Helmholtz frequency on mobility level of top plate (left panel) and sound pressure level (right panel). Mobility level is defined as 20 log (mobility/reference mobility). The four sets of curves represent, in order from top to bottom (1) normal guitar; (2) top plate loaded with 39.3 g; (3) "collar" inserted in soundhole; (4) soundhole plugged with wooden disk. Curves are displaced 25 dB for clarity. The horizontal lines through (the lower part of) each curve represent in the left panel a mobility level of −45 dB *re* 1 $mN^{-1}s^{-1}$, and in the right panel a sound pressure level of 55 dB, measured 2 m from the guitar in response to an exciting force of 0.2 N.

Mutual interaction of coupled resonances in guitars have been vastly explored in literature. Here an excerpt from the paper *"Simple model for low-frequency guitar function"*, Ove Christensen, Bo B. Vistisen, 1980

## 4.3 Are the frequencies of the first modes positioned in harmonic order?




In the plot here on the side we can observe the spectrum of the sound produced by the note A (fifth string): the fundamental frequency of this note is at 110Hz, the second harmonic stands out at a higher octave, 220 Hz, and then all the subsequent harmonics are evident. All the notes played on the instrument produce a large number of harmonics (depending on their physical characteristics, how the strings are made, etc.), and the general timbre of the instrument will

be characterized in large part by their amplitude and interaction with the other resonances of higher order. In this instrument the first two modes, at 105Hz and 180 Hz, are spaced between them less than an octave, far from the harmonic ratio, and do not overlap with the fundamental and the second harmonic of the played note. It is therefore always suggested that the main modes of the guitar should not have an octave ratio between them: to avoid interaction problems it is sufficient to space them a few Hz, approximately one or two semitones.

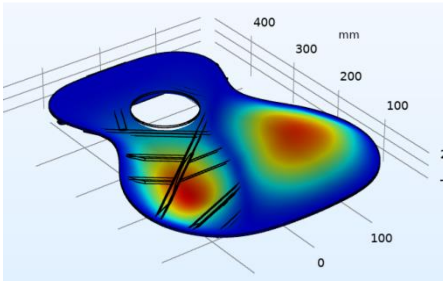
Similar reasoning must be carried out for the third mode T(1,1)3, the monopole of the back (if active). This mode is activated by the soundboard mainly through the resonance of the air volume, and therefore receives less energy than the soundboard (activated directly by the strings); in order for it to be maximally active it is needed to have a light back, resonating not too far in frequency from the mode T(1,1)2. At the same time, to prevent it from absorbing too much energy from the soundboard, possibly making the sound opaque and out of focus, it must not be too close: an ideal positioning is realized approximately for frequencies higher than T(1,1)2 of about three semitones.[6] Also for the T(1,1)3 resonance it is recommended to avoid overlapping to steer clear of wolfs notes. Usually the most simple and effective way to control and tune the frequency of this mode is by shaving the bracing system of the back, and also in this case it is suggested to aim for a higher frequency (keeping the bracing system higher than necessary during the assembly phase), and then gradually lower it during the final tuning of the completely assembled instrument, using a small fingerplane or a fine rasp tool, through the sound hole.

| String | frequency (Hz) | note | mode T(1,1)3 |
|---|---|---|---|
| 3 | 196,0 | G | |
| | | | 202 |
| | 207,7 | G# / Ab | |
| | | | 214 |
| | 220,0 | A | |
| | | | 226 |
| | 233,1 | A# / Bb | |
| | | | 240 |
| 2 | 246,9 | B | |
| | | | 254 |
| | 261,6 | C | |
| | | | 269 |
| | 277,2 | C# / Db | |
| | | | 280 |
| | 293,7 | D | |
| | | | 302 |
| | 311,1 | D# / Eb | |

[6] J.Meyer; *Quality aspect of the guitar tone; function, construction and quality of the guitar*. 1983

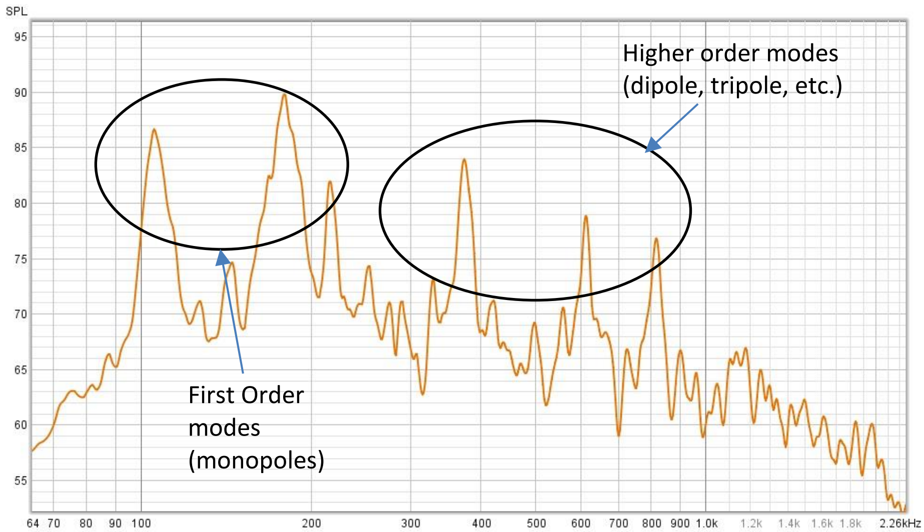
## 4.4 Presence and amplitude of higher-order modes

These are all resonances of the soundboard of a higher order than the first, when the soundboard doesn't resonate anymore similarly to a piston, but starts to break out into progressively smaller vibrating zones with different phase relationships among each other.



FEM simulation of the second order mode of the soundboard of an OM guitar with Martin-style X bracing. This mode is called cross-dipole, as it divides in two parts the lower bout of the instrument. Adjacent poles are always resonating in antiphase. It is also evident the slight asymmetry generated by the two classic oblique tone bars. This mode can produce a strong acoustic output and has a clear impact over the tone of the instrument.

We always start from the cross-dipole and long-dipole (which of the two intervenes first is a function of the active dimensions of the soundboard and the positioning of the bracing); then the tripole intervene, usually the first is the cross-tripole, and in very light and reactive soundboards we can also notice resonances that depend on even greater fragmentations. Controlling the shape and frequencies of the higher mode resonances is not simple, and often unnecessary: these resonances usually have a lower amplitude than the first modes, and as often noted in the literature, they "take care of themselves". Obviously when present they have a fairly evident influence on the sound of the instrument, and are the result of design choices related to the choice of the type of bracing, the lightness of the soundboard, the quality of all the assemblies and therefore the damping of all the mechanical joints of the instrument. In any case, it is interesting to observe their presence, check if there are any issues of wolf notes or strange vibrations corresponding to peaks; and of course to establish a correlation between these modes and the perceived sound offered by the instrument under analysis.

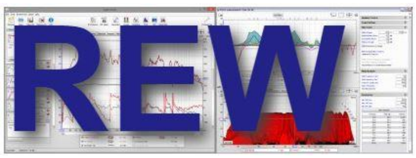


# 5 Appendix A

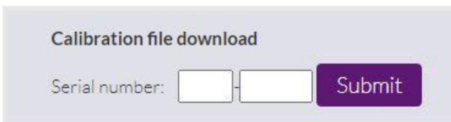
## The frequency response measurement setup

The frequency response measurement setup proposed in this document has been assembled following criteria of cost-effectiveness and ease of use; it uses only two main components (PC and USB microphone) no calibration is required, takes up minimal space and is portable.

The proposed microphone is the Umik-1 model by MiniDsp: https://www.minidsp.com/products/acoustic-measurement/umik-1 available for sale on the internet in various sites at a price of about 100 euros, is an omnidirectional measuring microphone connected via USB with an integrated AD converter. You connect it to your PC, and it's ready to use. A calibration file is also available on the manufacturer's website, certainly a very useful data; out of curiosity I used an expensive professional Neumann calibrator to check on my Umik-1 an adhesion of 0.3 dB at the reference level, an excellent performance in relation to the price. If you already have other microphones in your home leave them where they are; the investment necessary to equip yourself with a measurement microphone is in this case minimal, and the absence of an external audio interface greatly simplifies the use of the system in the workshop. Regarding the computer, I believe it is possible to use any product that has a free USB port; I obviously suggest a laptop, more convenient to be used in the workshop and easy to move around. The analysis software I recommend is REW (Room EQ Wizard), a freeware software that can be downloaded at this address: https://www.roomeqwizard.com/ and is available on both OSX and Windows platforms.

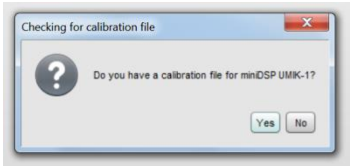




The implementation of the system is simple: from the MiniDsp website we download the custom calibration file of the microphone: https://www.minidsp.com/products/acoustic-measurement/umik-1



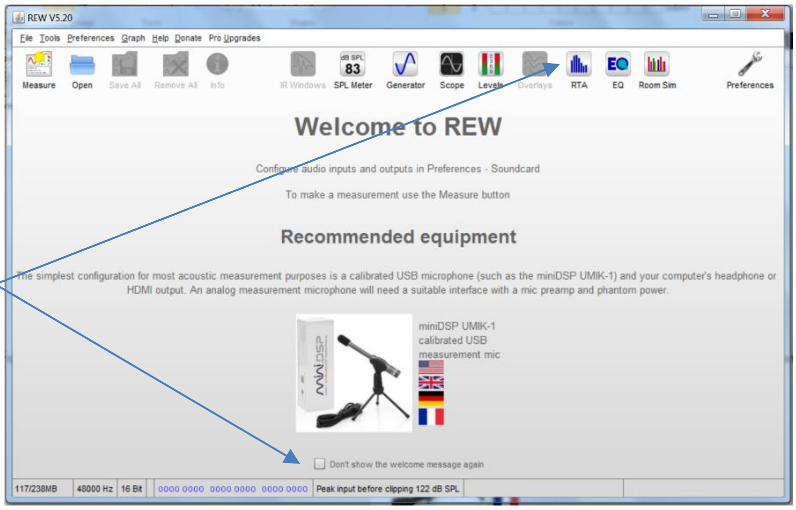

This file is already formatted for use with REW. We connect the microphone to a USB socket, launch the program, and this message immediately appear:

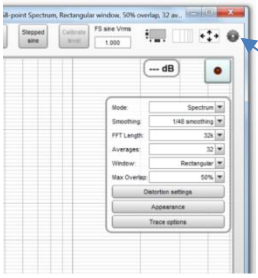
To which we will answer yes, to see this message appear immediately. Of course, we will provide the path of the calibration file previously saved in our main measurement folder.




At this point here we are on the main screen:

The software offers several features that we will not use at the moment, and we can ignore: we tick this box and directly launch the RTA (Real time analysis) function, the only REW tool that we will use for our measurements.




At the top right we find the preferences button, which opens the window on which we will have to enter the following parameters:

- **Mode**: spectrum
- **Smoothing**: to get a slightly cleaner display, we choose 1/48 octave. No more, otherwise the peaks become too blunt and we will lose useful information.
- **FFT length**: regulates the number of samples used to make the calculation of the FFT, the best balance for frequency response measurements is in my opinion 32k samples.
- **Averages**: allows you to averages a certain amount of measurements, to obtain a stable and repeatable curve we choose 32 measurements.
- **Windows**: is the type of time capture window used in the calculation of the FFT, we choose hann (short for hanning)
- **Max overlap**: lightens the processor while limiting the computational load of the FFT, we choose 50%

The system is now ready to go.

## 5.1 How to perform the measurement

There are several methods that allow to perform frequency response measurements of acoustic instruments, but there is no recognized and shared standard; over the last few years several studies have been carried out on the subject, with good results in terms of accuracy and precision, but very often unsatisfactory in terms of simplicity of execution and analysis of the results. The method that we propose in this tutorial has been optimized to have the maximum ease of use with the minimum investment, and is based on the acoustic measurement of the spectrum obtained by percussion of the instrument with an impact hammer around the bridge. This type of measurement is called "modal analysis", and is often used in architecture and engineering; when the hammer hits the structure of the guitar, a rapid impulse supplies energy to the structure, which is then excited in vibration. It is important that the energy supplied is evenly distributed across the frequency range of interests for our analysis (from 50 to 2000 Hz), that the overall energy provided by the impact hammer to the soundboard is consistent over different tappings – in order to be able to compare different measurements made on different instruments – and that the structure under analysis is always tapped around the same location.
Here are the most important setup parameters:

- The microphone must be directed towards the bridge of the instrument about 25cm away, about 80cm from the floor (perfect positioning on the edge of a table).
- The instrument must be tuned, the strings must be dampened by interposed foam or by hand: we can use earplugs for this purpose, but also just keeping the strings silent with the fingers can be a suitable technique.
- The instrument must be suspended from the ground, and the sound box free to vibrate on all sides (it can be held by the neck with the freehand).

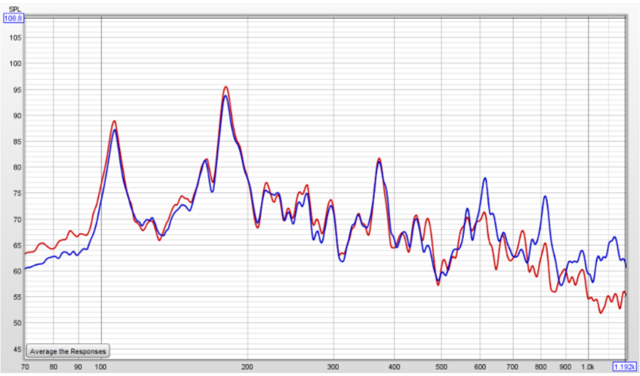
This is how we perform frequency response measurements in our workshop.

Once you press the start measure button (top right) you will start the percussion with delicate impacts, about a couple per second, for about 15 seconds. The resulting final curve you see on the screen is the average of all recorded percussions. During the measurement the instrument has to be kept at the same distance from the microphone. At the end of the 32 averages, we can quickly stop the measurement, using the same start button. A brief video of this procedure can be seen at: https://youtu.be/VSdMdGo7fPg

Two different types of impact hammer

The averaging method is the key that allows to obtain an accurate and repeatable measure, but of course it is important to keep a constant percussion energy and a stable distance of the instrument from the microphone (in my case I use a impact hammer of exactly 25cm as a ruler before beginning the measurement).

Others practical indications to perform a correct measurement are below. The type of hammer we use has an influence on the measurement; the relevant parameters are its weight and the material of the tip that will hit the instrument; the model that I use to measure wood parameters is a watchmaker one of 25 grams to which I added on the head a rigid rubber spacer. With this type of hammer, I get a very wide bandwidth, which allows to clearly visualize all the resonances of higher order, important to assess the characteristics of different types of wood. A second possibility that I suggest to measure complete instruments is to use a head made of Staedtler type eraser; the softness of the rubber reduces the bandwidth in high frequency, but the impact with the soundboard is certainly softer and more reassuring. I suggest starting with this type of hammer and if necessary, to analyze the behavior of the instrument in the high frequencies, to try to use a hammer of the first type. Once you have chosen your way, stick with the same type, to maintain consistency in the measurement process across the whole spectrum of frequencies and on the different instruments that will build your database.




Blue : watchmaker's hammer with rigid rubber tip
Red : rubber hammer, resonances at 610 and 820 Hz are less pronounced.

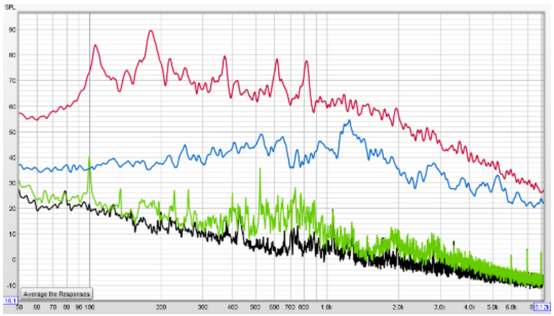
The force to be used is slightly higher than that of a tap-test, carried out with the fingers. The microphone is close enough to allow a very good signal to background noise ratio to be obtained. Try to train to get stable pulses along the 32 averages, which last about 15 seconds.

The zone where to hit with the hammer is around the bridge, in the surroundings of the saddle and the 6 pins. Depending on the shape of the higher order resonances there will a change in the response curve in frequencies above 200 Hz by moving on the wings of the bridge, or even outside the bridge. For the consistency of the measurements, we suggest to always stay in the central area as shown in the figure.

Tap over the 6 pins, to recreate the modal excitation of strings.

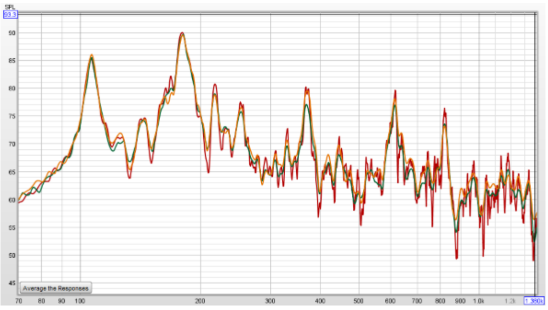
Once you have recorded the frequency response of the instrument it can be interesting to tap moving around the soundboard, to check which zone is responsible for higher order resonance modes.

Remember that in this type of measurement the background noise (the radio, a fan,etc.) is picked up by the microphone and can alter the curve; operate in a sufficiently quiet place.



Black : Background Noise
Green : Fan on
Blue: Solidbody Electric Guitar Response
Red: OM Acoustic Guitar Response

A little practice and confidence will allow you to make incredibly accurate and repeatable measurements (one of the most important criteria of the scientific method). The frequency tolerance of a resonance measurement should remain between +- 0.5 Hz, the average level tolerance of a curve around +-1 dB over the entire band.

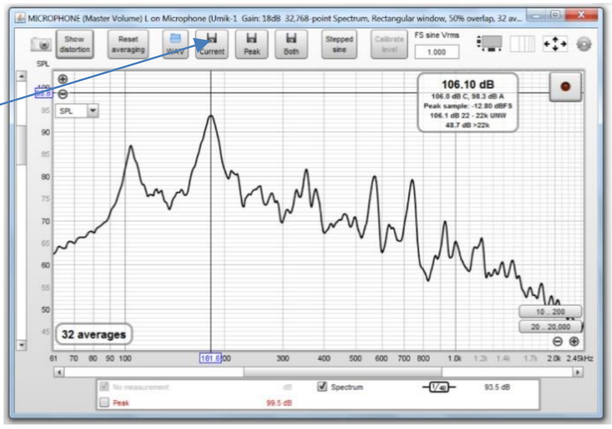


Three measurements of the same instrument repeated at short intervals.

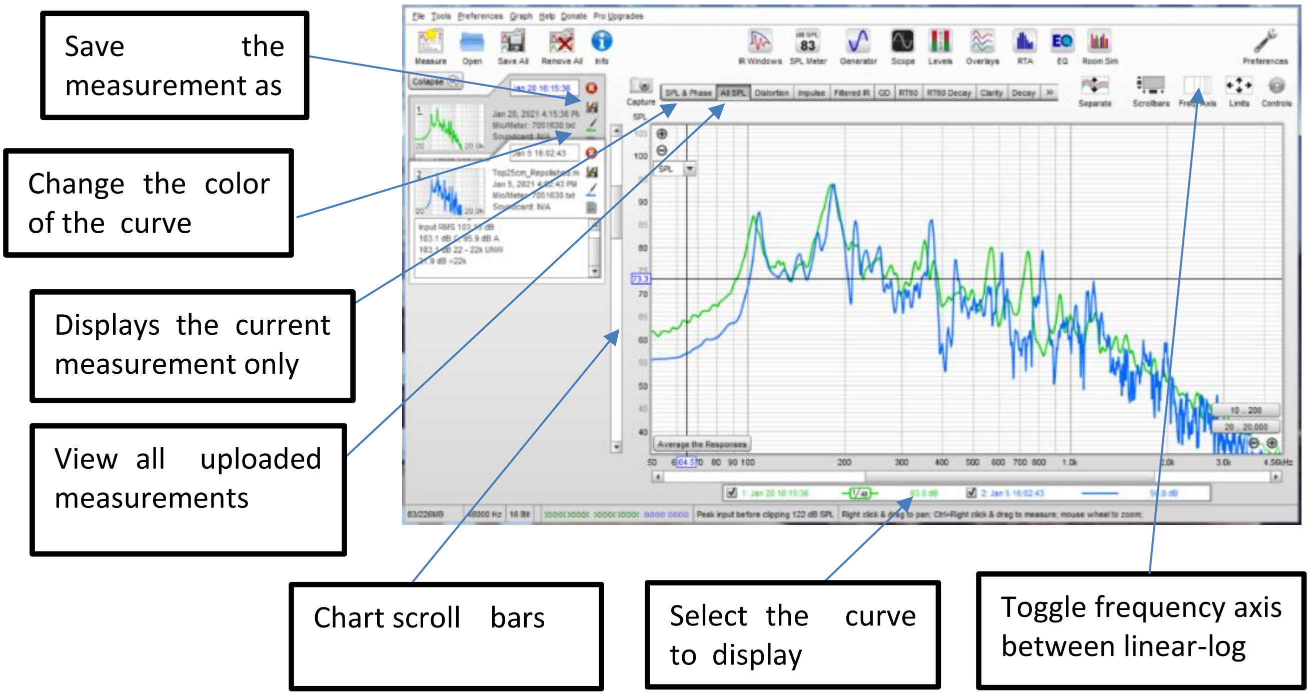
Every time you perform a new measurement, you should already have in mind an idea of the result you are going to get, and every time observe immediately the shape of the curve obtained: is it similar to what we expected? Are the frequencies of the main modes in the right places? Are the levels of the newly obtained curve reasonable and consistent with other similar measurements? At the base of a valid measurement database there is the principle that all the stored measurements have been validated.

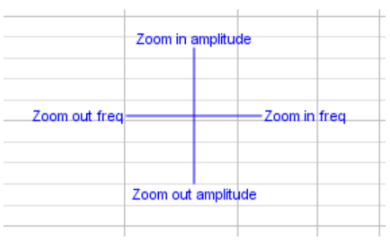
If you have any doubts, go back, check that everything is fine, repeat the measurement.

If possible, keep a reference instrument always available, together with its correct measurement, and in case of doubt use it to check that your measurement setup is working correctly. You will notice how stable a guitar can be over time, and you can check its slight changes according to the hygrometry of the moment. If all goes well, we should at this point see on the screen of the RTA analyzer a curve similar to this: by pressing the "current" button we save the curve on the main screen, from which you can then save it in the database, or view together with other curves.



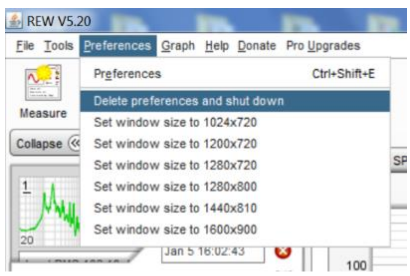
Some indications on the most useful functions of the main screen:




A very convenient function is available to zoom the curve: pressing and holding down the central button of the mouse (which I recommend using, it is also very useful to start and stop the measurement) the dynamic zoom tool appears, which you can adapt by moving the mouse in the four directions.

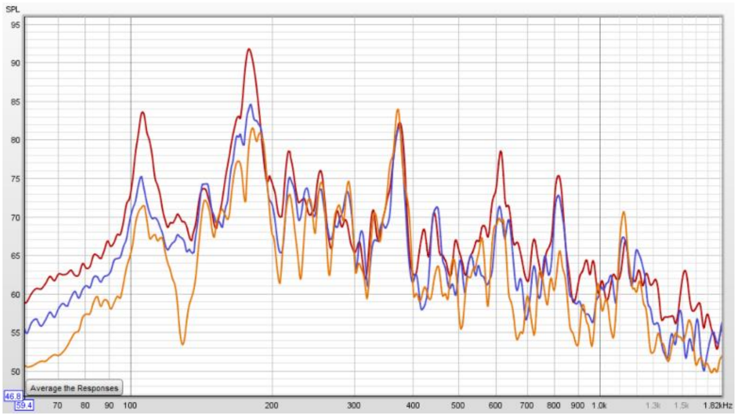
In case you find yourself in a situation of uncertainty, the measurements seem strange to you, you have made changes to the settings of the software without remembering exactly what, there is a function that allows you to reset all the settings and return exactly to the standard settings after the first installation. This feature is located in the preferences section of the main menu.




Finally, it is possible to export the curves for post-processing in text format through the "export" function of the main menu.

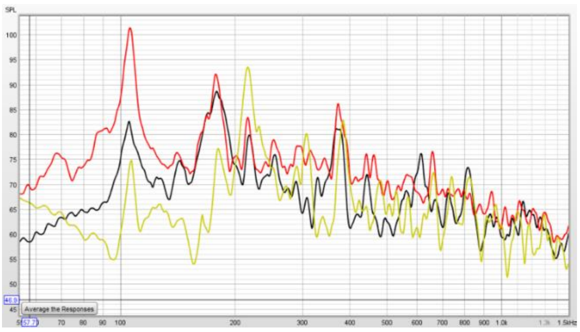
## 5.2 **Near field or far field?**

The distance of the microphone from the acoustic source plays a very important role. The microphone is considered "near field" when the distance from the source is less than the largest size of the sound-emitting surface; vice versa, the microphone is considered as placed in the far field. There is of course a "transition zone" between the two. To obtain a measurement that represents the acoustic emission of a guitar as heard by a listener in the audience it would therefore be necessary to place the microphone much farther than the 25cm that I suggest in these pages; but this setup would require an environment with an acoustic treatment that reduces the reflections of the walls, to obtain a clean and readable measurement. Otherwise - in a suboptimal acoustic environment, the situation that is usually found in a guitar making workshop - it is recommended to stay about 25 cm from the center of the soundboard, the bridge. Obviously if the measurement environment is optimal you can make different choices, what's important is: once you have established your standard, use always the same setup, to have the possibility to make correct comparisons. Waiting for the definition of a shared standard within the luthiery community.



Measurements at different distances of the same instrument: red – 25cm, blue – 50cm, yellow – 1m. As the distance increases, the reflections coming from the walls impact the curve and make it less readable. Note the different balance of the red curve compared to the yellow, especially in higher-order modes.

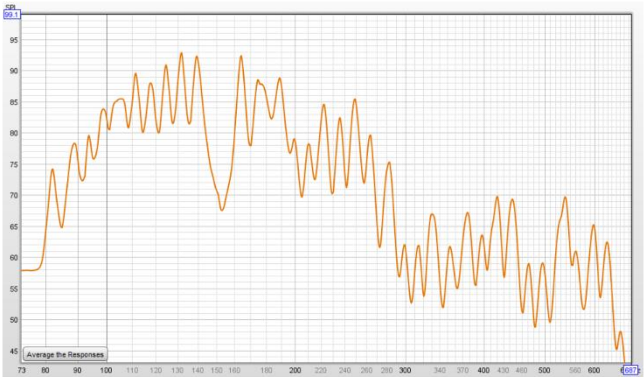
Getting even closer to the instrument is certainly possible, and it is indeed recommended in case you want to investigate localized resonances, or confirm the origin of some peaks of the response, as in the case of the contribution of the T(1,1)1 air resonance (with the microphone positioned flush with the opening), or in the case of the emission of the back and its T(1,1)3 mode.



The same instrument measured with different microphone positions:
red – flush with the opening of the rosette, highlighting the T(1,1)1 resonance, the air mode.
black - 25cm from the bridge.
yellow – 2cm from the center of the bottom, highlighting the T(1,1)3 resonance, the back monopole.

### 5.3 **Other types of measurement via microphone**

The simple measurement setup that we have described allows to also perform other types of measurement.




By reducing the number of averages to 4, inserting the "peak" function (present in the central bar below the graph) and playing some individual notes you can then view the fundamental frequency of the notes and the harmonics. This curve provides very interesting indications on the timbre balance of the instrument, since the first harmonic has a very important effect on the sensation of power of the fundamental, and this measurement allows to visualize the relative ratio on a fairly wide frequency band. Can you see in the graph above the influence of T(1,1)1 resonances on the cleanliness of contiguous notes and first harmonics?

In a similar way, once you have recorded a response curve and selected the first key always in the central bar below the graph that fixes it on the screen, you can "play on" the individual notes, to have a visual reference on the perceived sound, the perceptual sensation of the instrument, its frequency response and the sound emitted at that precise moment.

The microphone can also be used to measure the fundamental resonances of the wooden boards: this measurement allows you to view the harmonic content of the tap tone, and through simple calculations made in an excel sheet to derive mechanical parameters of the wood as Young's modulus and damping.

# 6 On the next update

- The monopole mobility
- Visualization of Chladni figures
- Measuring tonewood properties

# 7 Conclusions

A final note for the reader who is about to embark on the fantastic world of acoustic measurements, probably with suspicion and some fears: I still remember as if it were yesterday the first measurements made on a DIY loudspeaker, 25 years ago, with a Clio measuring system on which I had invested money set aside to go on holiday in Spain with my friends; the astonishment of "seeing" the sound appear on the computer screen, the feeling of finally having some certainties on which to rely and, immediately after, the disappointment of seeing that these points were not at all stable, but on the contrary they continued to move in all directions. Acoustic measurements, like all investigations that demand accuracy and repeatability, require attention, practice and goodwill. Although the configuration presented in this document is very simple and quite solid, the first times spent next to the microphone and the computer will certainly be difficult and it is important not to be discouraged, proceed with patience, method and rigor. The results will come soon, and it will be the beginning of a magnificent adventure…

Sorbiers, France, January 2022

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